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Long-baseline accelerator neutrino experiments

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Whole structure of the flavor-mass mixing in the lepton sector is now known through the measurements of neutrino oscillation. Remaining is the CP phase, which is yet totally unknown. One of the mixing angles, θ_{23} , is close to maximal mixing and its precise measurement is important to understand the origin of the flavor-mass mixing. The recent observation of ν_e appearance by the accelerator-based long-baseline experiment, T2K, opened a way to access the CP phase and CP violation in the lepton sector. Precise measurement of θ_{23} and determination of mass ordering are also expected with on-going and future accelerator-based experiment. Current status and prospects of accelerator-based long-baseline neutrino oscillation experiments are reviewed.

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1. Introduction

Quantum interference has been playing a unique role to examine the properties of quarks and neutrinos. However it appears in quite different scales for these two species. The time evolution of a mass eigenstate m_i is given as $e^{-i(Et-px)}$. Quarks can be treated approximately in a rest frame, hence $e^{-i(Et-px)} \approx e^{-im_it}$. This implies that the modulation frequency is determined by mass difference Δm and oscillation happens in nano to pico seconds. Neutrinos are ultra-relativistic particle due to its extremely light mass. So $e^{-i(Et-px)} \approx e^{-i\frac{m_i^2}{2E}L}$ and modulation frequency is governed by squared mass difference Δm^2 and the oscillation is observed in milli-second time scale or 100 km space scale for ~ 1 GeV neutrinos, which is a typical energy of accelerator-produced neutrinos. The interaction length of a 1 GeV neutrino in a 1g/cm^3 matter is 10^8 km, roughly corresponding to the distance between the Earth and the Sun. Therefore, it penetrates the Earth without being lost and reaches > 100 km away detectors.

Like the case of the quark sector, we now know that the weak flavor eigenstates, ν_e , ν_μ , and ν_τ are related to the mass eigenstates, ν_1 , ν_2 and ν_3 , by the unitary mixing matrix U :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

It is called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix, and is commonly parameterized as

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{+i\delta_{CP}} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with C_{ij} (S_{ij}) representing $\cos \theta_{ij}$ ($\sin \theta_{ij}$), where θ_{ij} is the mixing angle between the generations i and j . There is one irreducible phase, δ_{CP} , allowed in a unitary 3×3 mixing matrix. Then, one type of a flavor-eigenstate neutrino, ν_α , changes, after traveling a distance L , its flavor to β with an amplitude:

$$\langle \nu_\beta | \nu_\alpha(L) \rangle = U_{\beta i}^* U_{\alpha i} e^{-i\frac{m_i^2}{2E}L}. \quad (1.1)$$

From measurements of neutrinos from the Sun, reactors, atmosphere and accelerators, we know[1]:

$$\theta_{12} = 33^\circ \pm 1^\circ, \quad \theta_{23} = 46^\circ \pm 3^\circ, \quad \theta_{13} = 8.9^\circ \pm 0.4^\circ$$

$$\Delta m_{21}^2 = (7.5 \pm 0.2) \times 10^{-5} \text{eV}^2, \quad |\Delta m_{32}^2| = (2.44 \pm 0.06) \times 10^{-3} \text{eV}^2.$$

The θ_{23} is now most unknown. It is consistent with 45° , i.e., maximal mixing, within the uncertainty. We also don't know the order of mass, i.e., $m_1 < m_2 \ll m_3$ or $m_3 \ll m_1 < m_2$. The order would have a big impact on the neutrinoless double beta decay search, hence on the confirmation/refutation of the Majorana neutrino hypothesis. Most important unknown parameter is the CP phase δ_{CP} . It would cause CP violation in the lepton sector and can be a key to understand the origin of the matter-dominant universe. The value is totally unknown yet. Current and future

Table 1: Long-baseline experiments in the world

	proton beam energy	proton beam power (planned)	detector mass
K2K	12 GeV	7 kW	50 kt
MINOS	120 GeV	400 kW	5.4 kt
OPERA/ICARUS	400 GeV/c	500 kW	1.2 kt/0.6 kt
T2K	30 GeV	350 kW (750 kW)	50 kt
NOvA	120 GeV	420 kW (700 kW)	14 kt

accelerator-based long baseline neutrino experiments are aiming to do a precise measurement of θ_{23} , to determine the mass ordering and to explore CP violation in the lepton sector.

The experiment is conducted by producing a muon neutrino beam and measuring it at a $O(100)$ km away detector. In more detail, a proton beam from accelerators is injected to a target and pions are produced. Those pions decay in-flight and produce muon neutrinos. Electromagnetic horns are used to focus the pions in parallel by toroidal magnetic field and enhance neutrinos in the forward direction. By changing the polarity of the horns, either muon neutrino beam or muon antineutrino beam is produced. In case of the T2K experiment, which is introduced later, $\sim 1 \nu/\text{cm}^2/\text{s}$ penetrate the 295 km away far detector when the accelerator is operated at a 750 kW beam power.

The produced muon neutrinos then would change the flavor due to neutrino oscillation with the probability given as:

$$1 - P(\nu_\mu \rightarrow \nu_\mu) = \sin^2 2\theta_{23} \sin^2(\Delta m^2 \frac{L}{4E}),$$

where $\Delta m^2 \approx m_3^2 - m_2^2 \approx m_3^2 - m_1^2$, L is the distance between the neutrino production point and the far detector and E is the energy of the neutrino. Since $\sin^2 2\theta_{23}$ is close to one, most of muon neutrinos ‘disappears’. Among those, some are expected to appear as electron neutrinos with the probability:

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta m^2 \frac{L}{4E}). \quad (1.2)$$

Note that these probabilities are leading term and sub-leading terms follow. Recent reactor measurements give $\sin^2 2\theta_{13}=0.093$ [1], so only about 5% appears as electron neutrinos and dominant fraction changes into tau neutrinos and appear if energy is above the τ production threshold (~ 3.5 GeV).

2. World Long baseline neutrino oscillation experiments

The first long baseline neutrino oscillation experiment, K2K, started in 1999 in Japan with a 250 km baseline. Since then, number of experiments were or are being conducted. Table 1 summarizes those experiments. Most of these experiments intended or are intending to do a precise measurement of ν_μ disappearance and to search for or measure ν_e appearance.

Only the OPERA and ICARUS experiments have a neutrino beam whose energy is high enough to produce a tau. OPERA used nuclear emulsion as the far detector to tag the tau decay. ICARUS is a first experiment which realized large-scale ($300 \text{ ton} \times 2$) liquid Ar TPC's.

T2K and NOvA are running experiments.

T2K, in Japan, uses a neutrino beam produced with the J-PARC accelerator at Tokai and detects it with the Super-Kamiokande (SK) detector at Kamioka. The baseline length is 295 km and the peak energy of the beam is 0.6 GeV where the oscillation probability becomes maximum. The accumulated number of protons on target (POT), which is generally used as the statistics to represent the amount of data taken, is 7.0×10^{20} for the neutrino beam and 3.1×10^{20} for the antineutrino beam as of June 2015. The experiment is aiming to collect 78×10^{20} POT at the end. The Super-Kamiokande is a gigantic water Cerenkov detector. Events are classified with the number of observed Cerenkov rings and types of rings, i.e., a diffuse electron-like ring and a sharp muon-like ring. Single μ -like ring events are signal for ν_μ disappearance and single e-like ring events are signal for ν_e appearance. The separation of μ -like and e-like events is very good: mis-identification probability is about 1%.

NOvA uses a beam from the Main Injector at FNAL. The baseline length is 810 km and the beam peak energy is 2 GeV, which is slightly higher than the oscillation maximum (~ 1.6 GeV). NOvA's far detector is made of liquid scintillator. Extruded PVC tubes inserted with wavelength shifting fibers made up 344,000 cells and enable both tracking and calorimeter. The ν_e events or ν_μ events are selected with a showering or straight track, respectively.

3. Muon neutrino disappearance - Is θ_{23} 45° ?

The C.L. regions for $\sin^2 \theta_{23}$ and Δm_{32}^2 obtained primary from muon neutrino disappearance measurements are shown in Fig. 1[2]. The current most precise result is by T2K and obtained θ_{23} is $46^\circ \pm 3^\circ$.

4. Tau neutrino appearance

Disappearance of muon neutrinos from atmosphere or accelerators has been considered mainly due to ν_μ to ν_τ oscillation because only small portion appears as ν_e . This should be confirmed experimentally. The Super-Kamiokande collaboration reported the ν_τ appearance signal in the atmospheric neutrino samples with 3.8σ significance[3]. This is based on the excess in the enhanced τ -like events over background. The OPERA experiment is aiming to identify the τ production in the event-by-event basis. So far they observed four ν_τ candidate events and ν_μ to ν_τ oscillation is confirmed with a 4.2σ significance[4].

5. Electron neutrino appearance - Golden mode for CP phase and mass ordering -

As can be seen in Eq.1.1, the imaginary part vanishes in the probability of disappearance ($\beta = \alpha$). Hence measurements of appearance of particular type of neutrino are necessary to see CP violation in neutrino oscillation. Accumulation of tau neutrino appearance events is very difficult. An electron neutrino beam having energy above muon production threshold is not realized so far.

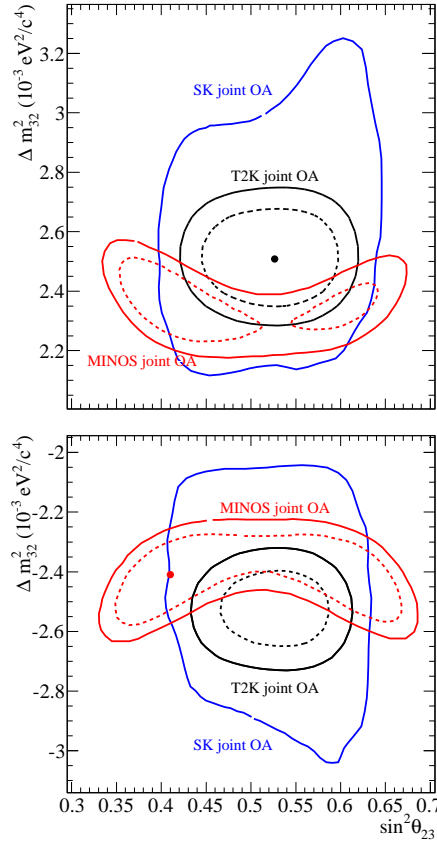


Figure 1: The 68% (dashed) and 90% (solid) C.L. regions for normal(top) and inverted(bottom) mass ordering[2]. Those shown are by T2K, MINOS accelerator experiments and by the Super-Kamiokande(SK) atmospheric neutrino measurement.

Therefore, appearance of electron neutrino from muon neutrino is the golden mode or practically a unique way to see CP violation in the lepton sector. Equation 1.2 shows the leading term only. A more exact ν_e appearance formula is given as

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) = & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \Phi_{31} (1 + \frac{2a}{\Delta m_{31}^2} (1 - 2S_{13}^2)) \\
 & + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta_{CP} - S_{12} S_{13} S_{23}) \cos \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} \\
 & - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta_{CP} \sin \Phi_{32} \sin \Phi_{31} \sin \Phi_{21} \\
 & + 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos \delta_{CP}) \sin^2 \Phi_{21} \\
 & - 8C_{13}^2 S_{13}^2 S_{23}^2 (1 - 2S_{13}^2) \frac{aL}{4E_\nu} \cos \Phi_{32} \sin \Phi_{31},
 \end{aligned}$$

where $C_{ij} = \cos \theta_{ij}$, $S_{ij} = \sin \theta_{ij}$, $\Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E}$ and $a \equiv 2\sqrt{2}G_F n_e E = 7.56 \times 10^5 \text{ eV}^2 \frac{\rho}{\text{gcm}^{-3}} \frac{E}{\text{GeV}}$ and ρ is the density of matter in which neutrinos propagate. The terms having a originate from the interaction between neutrino and matter and are called the ‘matter effect’. The equation includes only the first order for the matter effect. The probability for antineutrino is obtained by flipping the sign of δ_{CP} and a so the term with $\sin \delta_{CP}$ causes difference of the probability and hence CP

violation. At around the energy and baseline length where the probability becomes maximum and for $\sin^2 \theta_{23} = 0.5$, that CP-violating term causes at most $\pm 27\%$ difference in the oscillation probability. The matter-effect term contributes in the opposite way depending on the neutrino mass ordering. Thus, measurements of ν_e appearance have the sensitivity to determine the mass ordering, too. The ν_e appearance is observed with a 7.3σ significance by the T2K experiment with data obtained with 6.6×10^{20} POT in 2013[5]. This observation, 28 candidate events over 4.92 ± 0.55 background expectation, when combined with reactor measurements on $\sin \theta_{13}$ [1], enables us to put a constraint on possible δ_{CP} value. Figure 2 shows the credible regions for $\sin^2 \theta_{13}$ and δ_{CP} for T2K-only and T2K+reactor combined analyses. The statistics is too low to make any conclusion, but the result looks interesting with the best-fit point at the maximum CP-violation point. More data are highly desired.

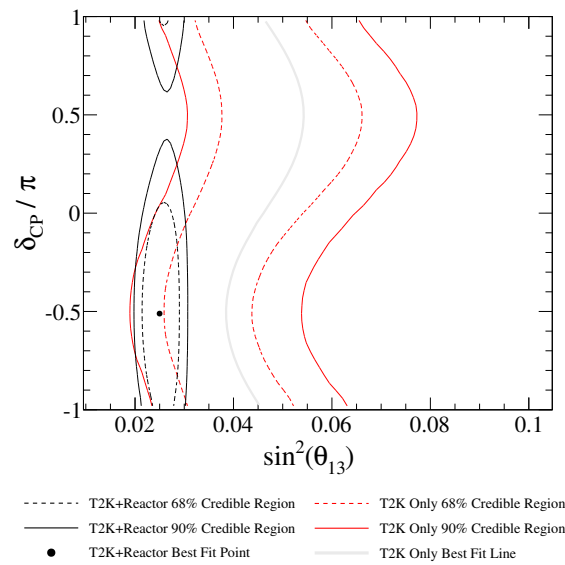


Figure 2: Credible regions for $\sin^2 \theta_{13}$ and δ_{CP} for T2K-only and T2K+reactor combined analyses[2].

6. Measurements with antineutrino

Measurements with antineutrino are more difficult because the cross section is smaller by factor of 2 to 3 compared to that of neutrino. However, the measurement of appearance with antineutrino is important and indispensable to explore CP violation. The CPT theorem imposes that the disappearance rate should be same for neutrino and antineutrino. So the comparison of disappearance between neutrino and antineutrino would be a unique test of new physics. The unknown non-standard interaction with the Earth matter during the propagation may cause difference in the accelerator-based long-baseline experiments. Since 2014, T2K has been accumulating data with the muon antineutrino beam. The first result of antineutrino disappearance obtained with 2.3×10^{20} POT is shown in Fig.3 together with that obtained with the neutrino beam. The result is consistent with that observed with neutrinos.

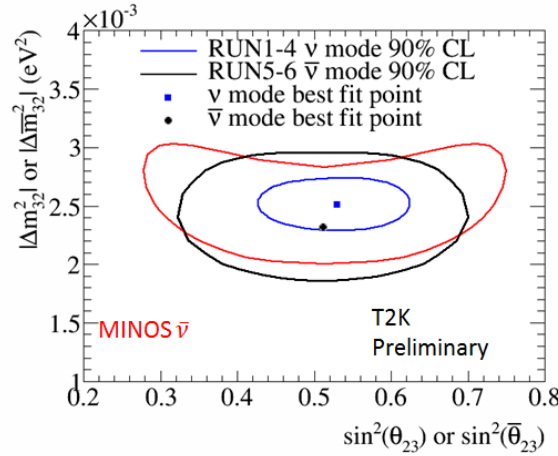


Figure 3: 90% C.L. for Δm_{32}^2 and $\sin^2 \theta_{23}$ obtained with T2K 6.6×10^{20} POT neutrino-beam data and 2.3×10^{20} POT antineutrino-beam data. MINOS antineutrino result[6] is overlaid.

7. Near future prospects

T2K has been accumulated 13% of the goal statistics so far. NOvA has just started and has 8% of the goal. What can be expected when these two experiments accumulated all the target data? The expected numbers of signal events at full statistics are $\sim 110 \nu_e$ and $\sim 20 \bar{\nu}_e$ for T2K and $\sim 70 \nu_e$ and $\sim 30 \bar{\nu}_e$ for NOvA. These numbers would be changed by 27% at most by the CP-violating term. The matter effect would change the numbers differently for T2K and NOvA because the baseline length and neutrino energy are different by about factor three for these two experiment. It is about 10% effect for T2K and 30% for NOvA. This difference, indeed, allows the sensitivities to CP violation and mass ordering be very much improved when results from the two experiment are combined. Figure 4 shows the sensitivities for CP violation and mass ordering both for individual experiments and combined case[7]. For favorable solutions, e.g., $\delta_{CP} = -90^\circ$ and the normal mass ordering, either of the two experiments has a 90% C.L. sensitivity for CP violation and NOvA has a good sensitivity to determine the mass ordering. When results are combined, sensitivities are enhanced and the mass ordering can be determined with 90% C.L. even for unfavorable parameter space. Therefore, at the end of these two experiments, we would expect some hints or even answer for CP violation and the mass ordering.

8. Summary

Since the discovery of neutrino oscillation and finite neutrino mass in 1998[8], our knowledge in this field has steadily evolved. We now know all the three mixing parameters and absolute values of the squared mass differences. What is remaining are the CP phase δ_{CP} , which is a key in the understanding of the matter-dominant universe, the value of θ_{23} , which is found to be very close to the maximal mixing case and the order of the masses. The observation of ν_e appearance by T2K opened a way to access δ_{CP} . The precise measurement of ν_μ disappearance showed that

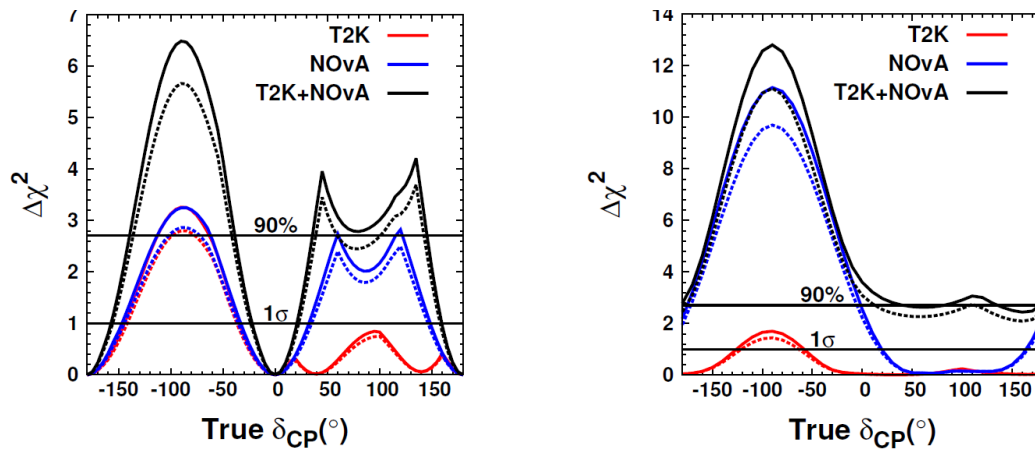


Figure 4: The sensitivity to the CP-violation, i.e., non-zero $\sin\delta_{CP}$, (left) and to the mass hierarchy discrimination (right) for various values of δ_{CP} for T2K (red), NOvA (blue) and T2K and NOvA combined (black) [7]. Solid curves correspond to sensitivities with statistical errors only, while dashed ones additionally with projected systematic errors. These sensitivities are for the case of $\sin^2\theta_{23} = 0.5$ and the normal mass hierarchy.

$\theta_{23} = 46^\circ \pm 3^\circ$. Accumulation of more data by T2K and NOvA may answer these open questions or further increase questions with unexpected observation in near future.

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